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AIRCRAFT CARRIER EXPOSURE TESTS OF ALUMINUM ALLOYS.(U)
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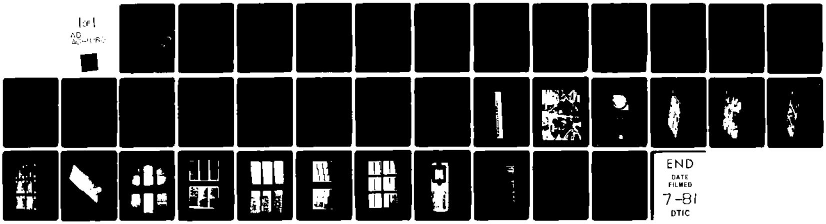

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An effort is underway to correlate results of accelerated laboratory corrosion tests with actual shipboard exposure of aircraft materials. This report describes the first of the series in which aluminum alloys with varying susceptibilities to exfoliation and stress corrosion were exposed on the flight deck of an aircraft carrier. Use of an electrochemical corrosion monitor to measure corrosivity of the environment is also described.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

A program is underway to determine quantitatively the corrosivity of the aircraft carrier environment by exposing a variety of materials on a carrier deck. The ultimate objective of the program is to develop an accelerated laboratory test that will more closely simulate that environment than do tests presently in use. The test will then be used to screen materials and protective finishes for Naval aircraft.

Permission was obtained to mount a rack on the radar platform of the U.S.S. John F. Kennedy, an area where it would be exposed to both stack gases and sea spray. It was decided for the first series of tests to use aluminum alloys that were available from a joint ASTM/Aluminum Association interlaboratory testing program. These alloys had been heat treated to provide varying susceptibilities to exfoliation and stress corrosion cracking and had been exposed to a variety of accelerated laboratory tests and natural environments, both marine and industrial. Therefore, their corrosion behavior had been well characterized and their use would allow for a comparison of the relative severity of a carrier environment with that of other marine environments.

An electrochemical device to measure corrosivity of the environment was also installed near the rack.

The work was performed under reference (a).

DESCRIPTION OF TESTS

MATERIALS

EXFOLIATION SPECIMENS

The aluminum alloys used for the exfoliation tests were supplied by Alcoa, Kaiser and Martin-Marietta and are listed in Table I.

The 2 inch plate of 2124 aluminum alloy was machined in three steps to expose the varying thicknesses (T) of T/10, T/4, and T/2. The ½ inch plate of 2124, the 7075 and 2024 extrusions were machined to expose the T/10 and T/2 planes. The 7178 aluminum alloy plate had only the T/10 plane exposed.

STRESS CORROSION SPECIMENS

Tensile specimens 1/8 inch in diameter, were machined from the short transverse direction of 7075, 2½ inch thick, aluminum alloy plate supplied by Alcoa. Tempers and heat numbers are as follows:

Temper	Expected Resistance To Stress Corrosion	Identification No.
T651	Low	S-395719
T7X51	Medium	S-396577
T7351	High	S-395721

Properties of the plate used were as follows: (from ref. b)

				Tensile Properties				
Temper	Electrical Conductivity, % IACS		Test Direction	Tensile Strength, ksi	(MPa)	Yield Strength, ksi	(MPa)	Elongation % in 4D
T651	surface	32.2	longitudinal	81.6	(563)	72.9	(503)	11.0
	T/10	31.5	long transverse	80.9	(558)	70.1	(483)	8.0
	T/2	32.6	short transverse	72.1	(497)	63.3	(436)	4.0
T7X51	surface	37.5	longitudinal	77.8	(536)	65.7	(453)	12.0
	T/10	37.1	long transverse	73.9	(510)	63.3	(436)	10.0
	T/2	38.7	short transverse	70.4	(485)	60.8	(419)	4.0
T7351	surface	41.0	longitudinal	67.0	(462)	55.1	(380)	10.0
	T/10	40.6	long transverse	66.0	(455)	54.5	(376)	10.0
	T/2	41.0	short transverse	59.1	(407)	51.7	(356)	4.0

PREPARATION FOR EXPOSURE TESTS

Exfoliation Specimens

Exfoliation specimens were prepared as follows:

1. Degreased with solvent
2. Etched in 5% by weight NaOH at 80°C (176°F), 1 to 3 min.
3. Rinsed in water
4. Desmutted in concentrated HNO_3 for 30 sec.
5. Rinsed in deionized water
6. Dried with oil free air

Stress Corrosion Specimens

Specimens, stressing fixtures and method of stressing are illustrated in figure 3 of ASTM G49. (reference c).

After stressing in frames that had been sulfuric acid anodized and sealed, the frames were painted with MIL-P-23377 epoxy primer and MIL-C-81773 polyurethane topcoat. The ends were dipped in the paint to protect the threads. Only the gage length was left unpainted. The specimens were then degreased prior to exposure.

Stress levels used were as follows:

T651 - 25, 15, 8 ksi
T7X51 - 45, 35, 25 ksi
T7351 - 43 ksi

Triplicate specimens were exposed at each stress level.

Exposure Rack

A steel rack, 8 feet by 1 foot, was fabricated, cadmium plated, chromated and painted with MIL-P-23377 epoxy primer and MIL-C-81773 polyurethane

topcoat. The rack was designed so that the specimens would be exposed at an angle of 45° from the vertical. Exfoliation specimens were mounted on the rack with plastic bolts. MIL-S-8802 polysulfide sealant was applied around the bolts to avoid crevice corrosion. The rack with the specimens attached is shown in figure 1. The rack was then welded onto the radar platform. Figure 2 shows the rack in place on the carrier.

The carrier was deployed to the Mediterranean for eight months from June 1978 to March 1979. During the first month the specimens were inspected at 9, 16, and 26 days by carrier personnel, then at four and eight months by NADC personnel. Exact times to failure, therefore, are not available.

At the end of eight months the ship returned and went into dry dock, so the specimens had to be removed at that time.

Electrochemical Corrosion Monitor

The corrosion monitor probe is a galvanic couple made of several plates of aluminum and steel. The principle of operation is based on the dissimilar metals being wetted by condensed moisture of the atmosphere or rain thereby creating an electrical current which can be measured. The metal plates are sandwiched together alternately and separated by the electrical insulator spacers. The parallel plates so bolted together were short circuited by two electrical conductors (aluminum to aluminum and steel to steel) and ending with two terminals, one for aluminum and the other for steel. The whole array of these plates was then potted in epoxy leaving only one long edge surface exposed. A photograph of this probe in shown in figure 3 (a). The unpotted surface was later surface ground and polished to a 600 grit finish. There were 10 plates of each metal, approximately 0.8 inch long and 0.02 inch thick. The total exposed surface area for each metal (aluminum or steel) was nearly equal in size, approximately 1 inch. The galvanic coupling of the probe was done externally through a long shielded cable to a low resistance potential monitoring system as shown in figure 3 (b). Here the potentiostat serves as a zero resistance ammeter in which the voltage (V) between the working (W) and the reference (R) terminals of the potentiostat was set to zero and the reference (R) and the counter (C) terminals were short circuited through a resistor (Rs). A high impedance strip chart recorder was connected across this resistor which directly measured the galvanic current developed by the probe. The details of the operation and principles of this technique are reported elsewhere. See reference (d).

The probe was installed near the exposure rack about 20 feet above the flight deck on a radar tower. The current measuring instruments were located in the radar room to isolate them from the flight deck environment. The sensitivity of the recorder was set low so that at high relative humidity (~80%), the output of the probe was reading approximately 5 microamps. Thus, the full scale range setting on the recorder could measure up to 500 microamps output of the probe. At the end of the mission the current-transients recorded on the chart paper were analysed and condensed in order to evaluate the results.

Salt Spray Tests

Salt spray tests were conducted in 5 per cent $NaCl/SO_2$ and 5 per cent Synthetic Sea Salt (SSS)/SO_2 according to the procedure in reference (e) on the 2124 plates and the 7075 extrusions to compare type of attack with the carrier samples. The angle of inclination was 45° from the vertical.

RESULTS AND DISCUSSION

Exfoliation Tests

Results of the exfoliation tests on the carrier are given in table II. The panels were evaluated using the ASTM G34 rating system. The appearance of the panels is shown in figures 4 to 8.

In general the results showed the same trend as those obtained for the same alloys and tempers in the ASTM/Aluminum Association interlaboratory testing program in both natural environments and laboratory tests. (reference (f)). Those tempers that exfoliated in the other environments also exfoliated on the carrier. There were some anomalies however. For example, the medium resistance 7075 extrusion had more exfoliation on the T/10 surface than on the T/2. This same result was reported at the end of 5 months exposure at Point Judith, Rhode Island but not in any of the laboratory tests or after longer marine exposures. Also the medium resistance ½ inch, 2124 specimen exfoliated on the T/10 plane but not the T/2.

In the ASTM/Aluminum Association interlaboratory program, the 1/2 and 2 inch thicknesses of 2124 plate were reported to exhibit similar behavior in marine environments. The same result was evident in the carrier tests.

Results of salt spray tests are given in table III. Appearance of the panels is shown in figures 9 to 13. Comparison with figures 4 to 8 clearly show a difference. The panels exposed on the carrier lack the general or surface attack that occurred on the salt spray panels. On the carrier panels, exfoliation attack initiated at the machined edges and essentially undermined the surface. The distinct layering that occurred on the carrier samples did not occur on the salt spray panels although exfoliation attack is present on low and medium resistance tempers.

The same distinct layering seen on the carrier samples occurred also on the low and medium resistance 2124 plate of both thicknesses when exposed to the industrial atmosphere at the McCook plant of Reynolds Metals Co., Brookfield, Illinois.

The surfaces of the carrier samples were badly discolored. Deposits on the specimens were analyzed by infrared spectroscopy and energy dispersive spectrometry, and found to consist largely of MIL-L-23699 engine oil deposits. Sulfur was also identified.

Inquiry to COMNAVAIRLANT elicited the information that the high winds frequently encountered on the flight deck could transmit oil particles that escape during engine oiling operations. The possibility that a thin film of

such oil could inhibit surface attack was subsequently checked by $NaCl/SO_2$ spray test. No inhibition was apparent.

Exfoliation was also noted on the underside of the following carrier specimens:

2124 - ½ inch low and medium resistance
2124 - 2 inch low and medium resistance
7178 - low resistance

This behavior was also noted in the Point Judith marine exposures.

Stress Corrosion Tests

Times to failure are presented in table IV.

Results on the same alloy and tempers in two other natural environments are shown in table V which is taken from reference (b). Reference (b) contains the results on the entire interlaboratory testing program on the 2½ inch, 7075 plate. Times to failure for the T651 and T7X51 tempers on the carrier are analogous to those at Cape Canaveral.

Metallographic examination was made on one broken specimen from each stress level. Findings were as follows:

T651 temper	25 ksi	-	no secondary cracks
	15 ksi	-	several secondary cracks
	8 ksi	-	many secondary cracks

T7X51 temper - 45, 35, and 25 ksi - few secondary cracks

Figure 14 shows the appearance of the stress corrosion fixtures after four months exposure before and after cleaning, demonstrating clearly the dirt and discoloration from the carrier environment.

Corrosion Monitor - The tracings of the current transients recorded over eight months of exposure were replotted to obtain a condensed form of graph for better appreciation of the results. As shown in figure 15, the plot of galvanic current, Ig, against exposure time in days exhibits several periods of high corrosion activity (currents). In the first 40 days, the corrosion monitor showed less than 10 microamps. Between 50 and 120 days there appeared to be periods of wetness, but in the last 100 days considerable corrosive activity is indicated with currents as high as 500 microamps. This correlates with reports from carrier personnel that the weather in the first 4 months of deployment was generally mild, whereas that of the last 4 months was characterized by storms and high seas.

Results obtained with the probe in the $NaCl/SO_2$ salt fog chamber help to interpret the carrier records. The salt spray test involves constant spray of 5 per cent NaCl with introduction of SO_2 gas into the chamber for 1 hour in every 6. High current peaks were recorded only during the hours when the SO_2 was entering the chamber. The peaks then are indicative of extremely corrosive conditions in the environment. When an integrated analyses of extremely high current periods was made, the results (as determined from

figure 15) showed that approximately 27 days out of 250 the ship experienced the most corrosive conditions with corrosion currents greater than 300 microamps. This value is almost 100 times greater than the value obtained by the corrosion monitors in only high humidity environment.

CONCLUSIONS

1. Results of the exfoliation and stress corrosion tests indicate that the environment of a conventional aircraft carrier is highly corrosive.

2. Modification of the NaCl/SO_2 salt fog test is required to duplicate the highly localized nature of exfoliation attack which occurred on the susceptible alloys on the carrier and to minimize the general surface attack characteristic of the salt fog test.

3. The corrosion monitor shows promise for quantitatively assessing the corrosivity of any atmospheric environment.

FUTURE PLANS

A rack has been installed on the nuclear powered U.S.S. Nimitz. The rack contains graphite epoxy composites, laser hardened coatings, and some avionics components along with control specimens of the aluminum alloys used in the tests described in this report. This new effort will provide an opportunity to compare carrier environments with and without sulfur containing stack gases.

A rack is being prepared for installation on another carrier in the Atlantic fleet and one in the Pacific fleet as well. This will permit an assessment as to whether one theatre of operation is more severe than the other from an environmental standpoint.

TABLE I

ALUMINUM ALLOYS USED FOR EXFOLIATION TESTS

Alloy/Form	Temper	Thickness (inches)	Expected Resistance to Exfoliation	Identification	Dimensions
2124 Plate	T851	0.5	High		3" x 6"
	T351	0.5	Intermediate		3" x 6"
	T351+	0.5	Low		3" x 6"
	T851	2.0	High	665611	3" x 6"
	T351	2.0	Intermediate	"	3" x 6"
	T351+	2.0	Low	"	3" x 6"
7075 Extrusion		0.5	High	5832	3" x 3"
		"	Intermediate	5831	3" x 3"
		"	Low	5830	3" x 3"
2024 Extrusion			High	5102-3	2" x 6"
7178 Plate	T6	.091	Low	371774-1-2	3" x 6"
	T6 + 10 hrs at 325°F	.091	Intermediate	371774-10-2	3" x 6"
	T6 + 11 hrs at 325°F	.091	High	371774-11-2	3" x 6"

P - Pitting

EA - Superficial exfoliation - tiny blisters, thin slivers, flakes or powder, with only slight separation of metal.

EB - Moderate exfoliation - appreciable separation of metal with notable penetration.

EC - Severe exfoliation - pronounced lamellar attack extending a considerable depth into the metal.

ED - Very severe exfoliation - very severe lamellar attack.

EXPLANATION OF RATING SYSTEM FROM ASTM G34 USED IN TABLES II AND III

TABLE II

RESULTS OF EXFOLIATION TESTS ON AIRCRAFT CARRIER

June 1978 - March 1979

ALLOY/EXPOSURE PERIOD	LOW RESISTANCE			MEDIUM RESISTANCE			HIGH RESISTANCE		
	T/10	T/4	T/2	T/10	T/4	T/2	T/10	T/4	T/2
2124-2" plate/4 mos.	EB	EB	EA	P	EA	EA	P	P	P
2124-2" plate/8 mos.	ED	ED	EC	P	EC	EC	P	P	P
2124-1/2" plate/4 mos.	EA	--	EA	EA	--	P	P	-	P
2124-1/2" plate/8 mos.	ED	--	EC	EC	--	P	P	-	P
7178 plate/4 mos.	EA			P			P		
7178 plate/8 mos.	ED	--	--	P	--	--	P	-	-
7075 extrusion/4 mos.*	EB	--	EA	EA	--	P	P	-	P
7075 extrusion/8 mos.*	ED	--	EB	EB	--	P	P	-	P
2024 extrusion/4 mos.							P		P
2024 extrusion/8 mos.							P	-	P

NOTE: All exfoliation attack originated at edges; particularly machined edges.

* Duplicate samples

T/10 plane refers to plane exposed when one tenth of the thickness is removed from the plate;
T/2 when one half the thickness is removed.

TABLE III

SALT SPRAY TEST RESULTS

2124 - 2" PLATE

Exposure Time	Low Resistance NaCl/SO_2 T/10	T/4	T/2	Low Resistance SSS/SO_2 T/10	T/4	T/2	Medium Resistance NaCl/SO_2 T/10	T/4	T/2	Medium Resistance SSS/SO_2 T/10	T/4	T/2	High Resistance NaCl/SO_2 T/10	T/4	T/2	High Resistance SSS/SO_2 T/10	T/4	T/2
10 days	EC	EC	EC	EA	EA	EB	EC	EC	EC	EA	EA	EA	P	P	P	P	P	P
20 days	EC	EC	EC	EA	EA	EB	EC	EC	EC	EB	EB/EA	EA	P	P	P	P	P	P
30 days	EC	ED	ED	EA	EA	EB	EC	EC	EC	EB	EB	EB	P	P	P	P	P	P
37 days	EC	ED	ED	EC	EC	EC	EC	EC	EC	EC	EC	EC	P	P	P	P	P	P
2124-½" PLATE																		
	T/10		T/2	T/10		T/2	T/10*		T/2	T/10		T/2	T/10		T/2	T/10		T/2
10 days	EA		EB	EA		EA	PB		P	P		P	P		P	P		P
20 days	EB		EC	EA		EA	EB		EA/EB	P		P	P		P	P		P
30 days	EC		EC	EB		EB	EC		EB	P		EA/P	P		P	P		P
37 days	EC		rosettes ED	EC		EC	EC		EB	EB		EB	P		PB	deep P		deep PB
7075 EXTRUSION																		
10 days	P		EA	P/EA		P/EA	EB		EB	P/EA		P/EA	EA		EB	P/EA		EB
17 days	EC		ED	EB		EC	EC		ED	EB		EC	PB		PB	P/EB deep pits		P/EB

* T/10 in medium resistance has more attack than T/2.

TABLE IV

RESULTS OF STRESS CORROSION TESTS ON AIRCRAFT CARRIER

7075 Aluminum Alloy

Temper	Stress Level	Spec. No.	Days to Failure
T651	25	1	Between 9 and 16
		2	< 9
		3	< 9
	15	4	< 9
		5	< 9
		6	< 9
	8	7	Between 9 and 16
		8	Between 9 and 16
		9	< 9
T7X51	45	10	Between 26 and 35
		11	Between 9 and 16
		12	Between 9 and 16
	35	13	Between 9 and 16
		14	Between 9 and 16
		15	Between 9 and 16
	25	16	Between 16 and 26
		17	Between 16 and 26
		18	Between 16 and 26
T7351	43	19)	
		20) -	No failure in 8 months
		21)	

TABLE V (taken from ref. (b))

Summary of Atmospheric Stress-Corrosion Tests of 7075 Alloy Plate.

Plate Temper	Applied Stress, ksi	Specimen Configuration	Seacoast Atmosphere (Cape Canaveral) Exposed 3 Nov. 1971 F/N	Days to Failure	Exposed 3 May 1972 F/N	Days to Failure	Industrial Atmosphere (Philadelphia, Pa.) Exposed 12 Nov. 1971 F/N	Days to Failure	Exposed 2 May 1972 F/N	Days to Failure
T651	25	0.125 in. tension (3.18 mm)	5/5	5,5,7,7,7	5/5	1,2,2,2,5	5/5	130,163,204, 208,229	5/5	37,37,42,50,66
	15 (100 MPa)	0.125 in. tension (3.18 mm)	5/5	5,7,9,12,22	5/5	5,5,5,6,27	5/5	155,229,242, 499,649	5/5	71,466*,487*, 487*,408**
	8 (55 MPa)	0.125 in. tension (3.18 mm)	4/5	18,26,90,93	4/5	6,6,6,27	1/5	149	0/5	
T7X51	45 (310 MPa)	0.125 in. tension (3.18 mm)	5/5	30,37,37,55,70	5/5	5,9,27,76, 76	2/5	966,1039	2/5	543,670
	35 (240 MPa)	0.125 in. tension (3.18 mm)	4/5	37,545,<730,855	2/5	282,342	1/5	566	0/5	
	25 (170 MPa)	0.125 in. tension (3.18 mm)	2/5	30,107	0/5		0/5		0/5	
T7351	43 (300 MPa)	0.125 in. tension (3.18 mm)	0/5		0/5		0/5		0/5	

NOTES-1. Intended inspection schedule: < 30 days, daily
30-60 days, twice a week
60-365 days, weekly
>365 days, monthly
2. Status of tests updated June 1975.
3. *Removed at 408 days and reloaded. **Broke during reloading.

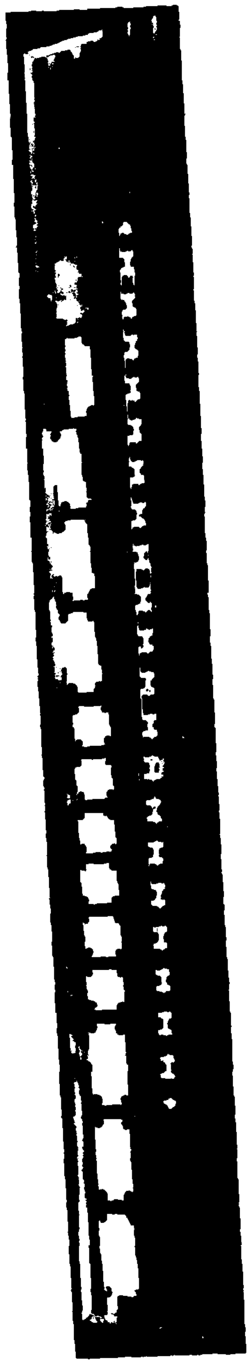


Figure 1 - Rack for Carrier Exposure with Specimens Installed.

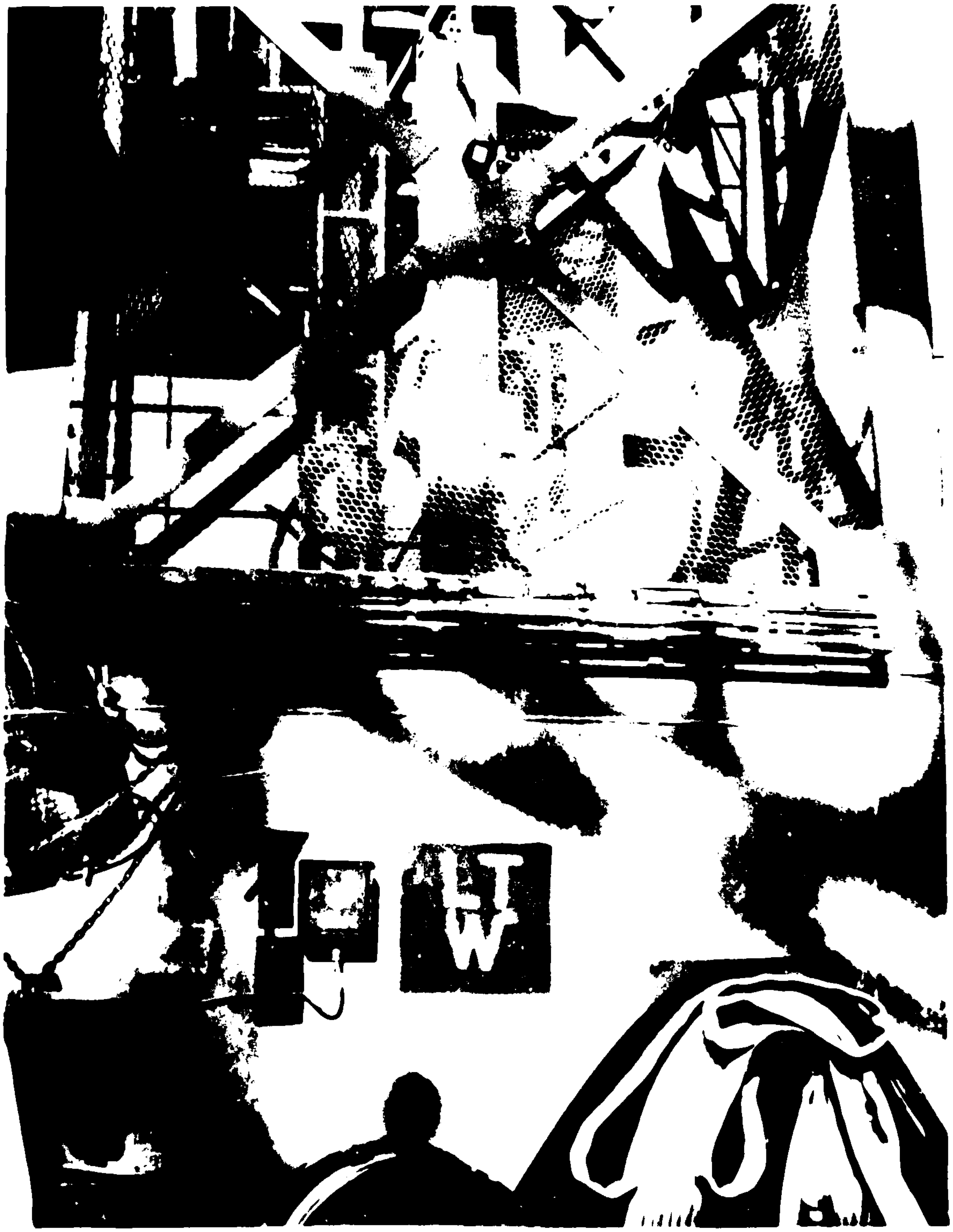


Figure 2 - Rack Installed on Radar Platform.

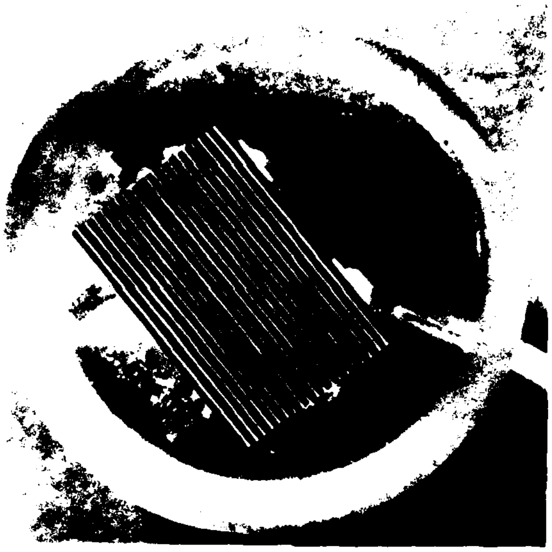


Figure 3 (a) - Photograph of Monitor Showing Placement of Aluminum and Steel Plates.

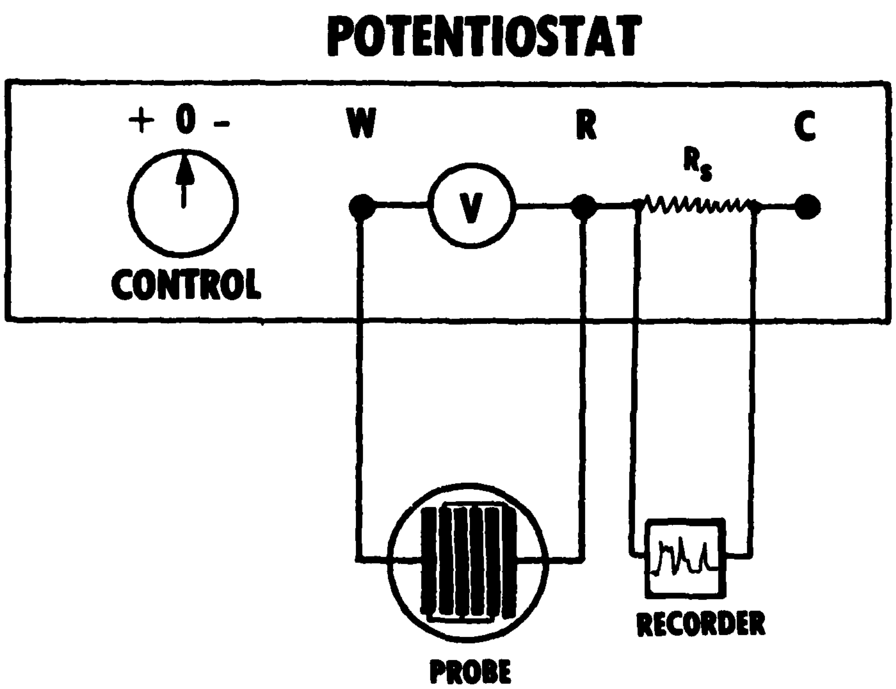
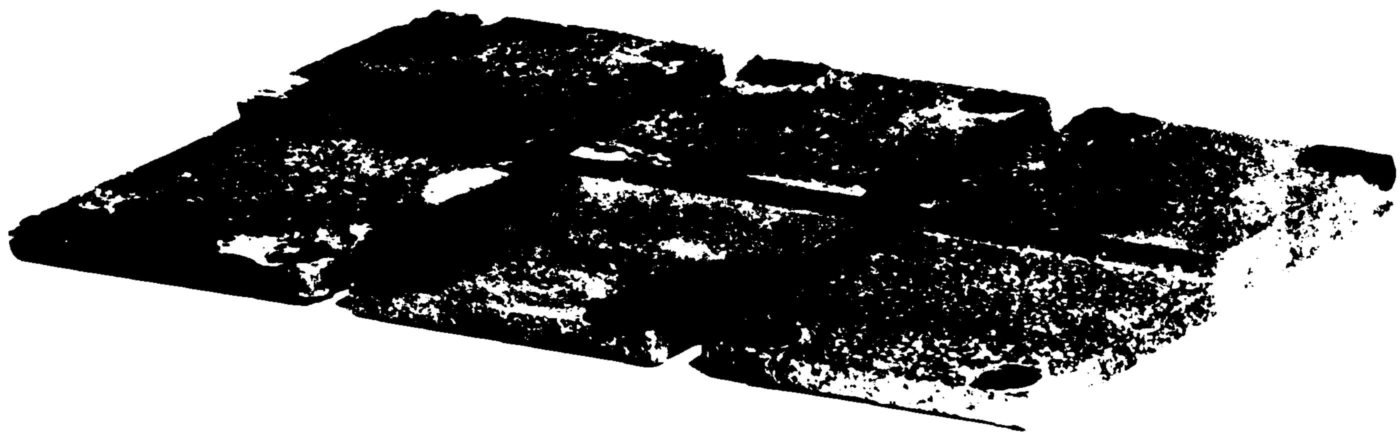
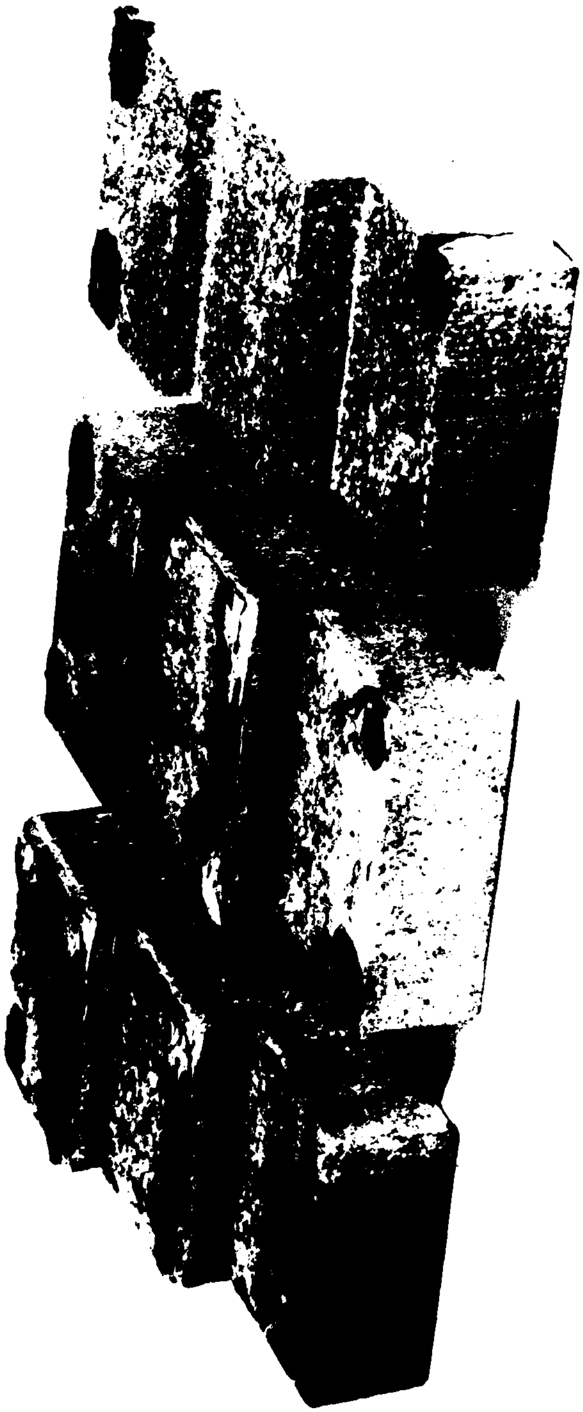


Figure 3 (b) - Circuit Diagram



LEFT - LOW RESISTANCE
MIDDLE - MEDIUM RESISTANCE
RIGHT - HIGH RESISTANCE

Figure 4 - 2124-1/2 in. Plate After 8 Months on Aircraft Carrier.

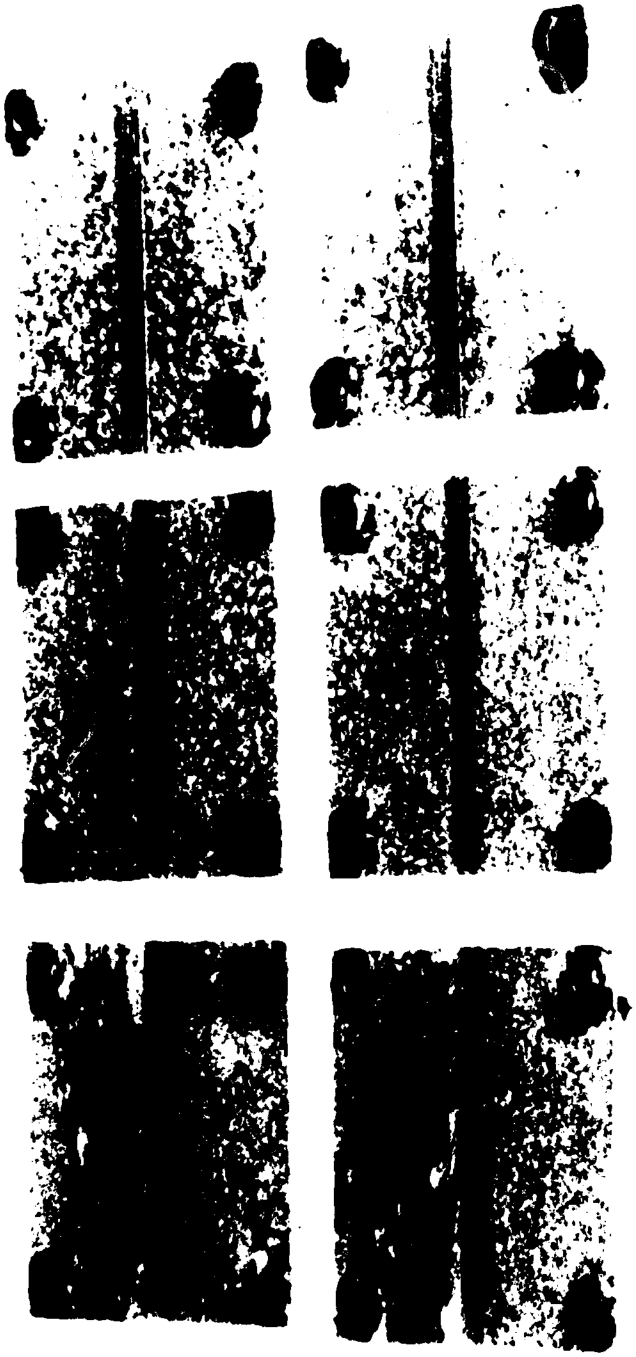


LEFT - LOW RESISTANCE
MIDDLE - MEDIUM RESISTANCE
RIGHT - HIGH RESISTANCE

Figure 5 - 2124-2 in. Plate, After 8 Months on Aircraft Carrier.

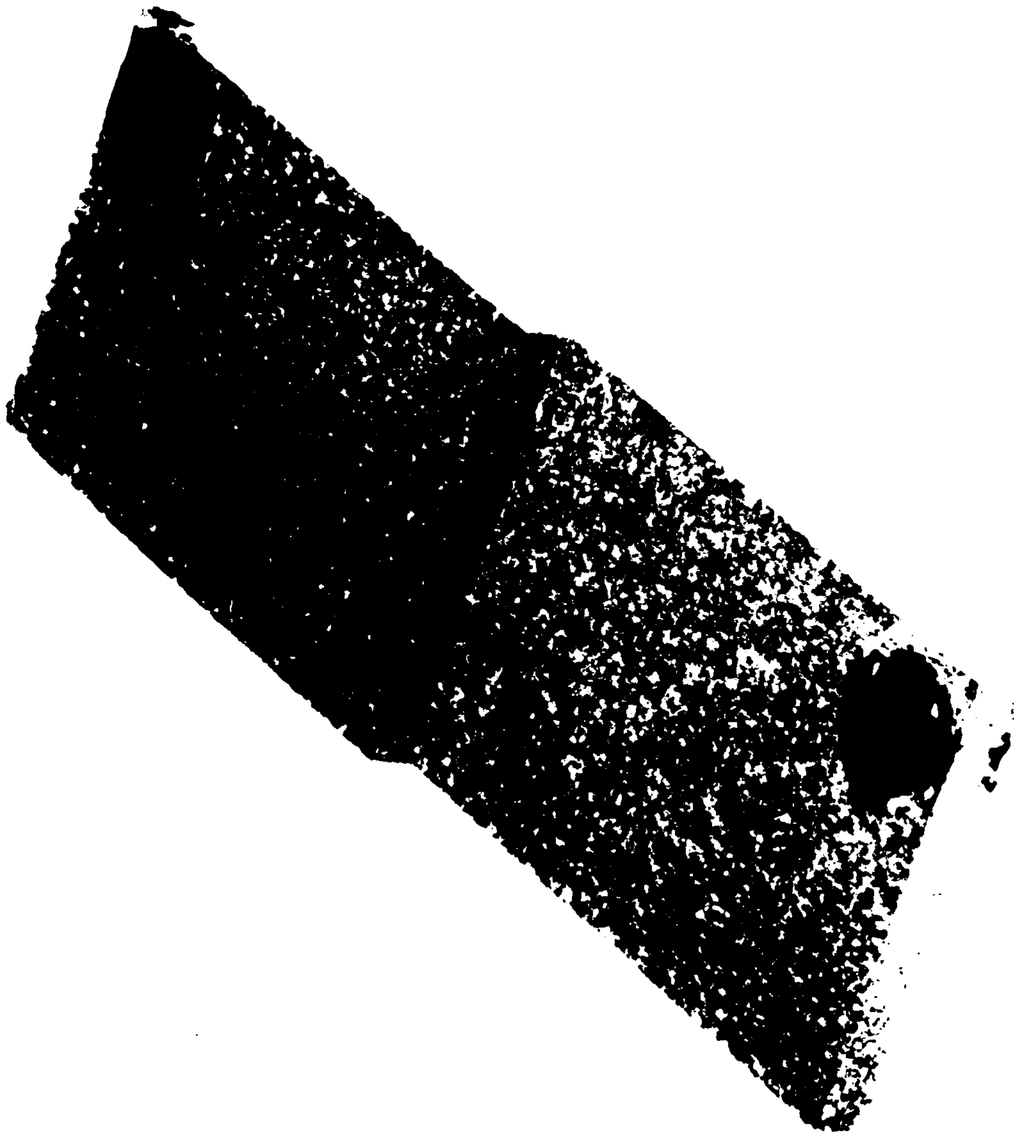
LEFT - LOW RESISTANCE
MIDDLE - MEDIUM RESISTANCE
RIGHT - HIGH RESISTANCE

Figure 6 - 7178-.091 in. Plate, After 8 Months on Aircraft Carrier.



LEFT - LOW RESISTANCE
MIDDLE - MEDIUM RESISTANCE
RIGHT - HIGH RESISTANCE

Figure 7 - 7075- 1/2 in. Extrusion, After 8 Months on Aircraft Carrier.



HIGH RESISTANCE

Figure 8 - 2024 Extrusion, After 8 Months on Aircraft Carrier.

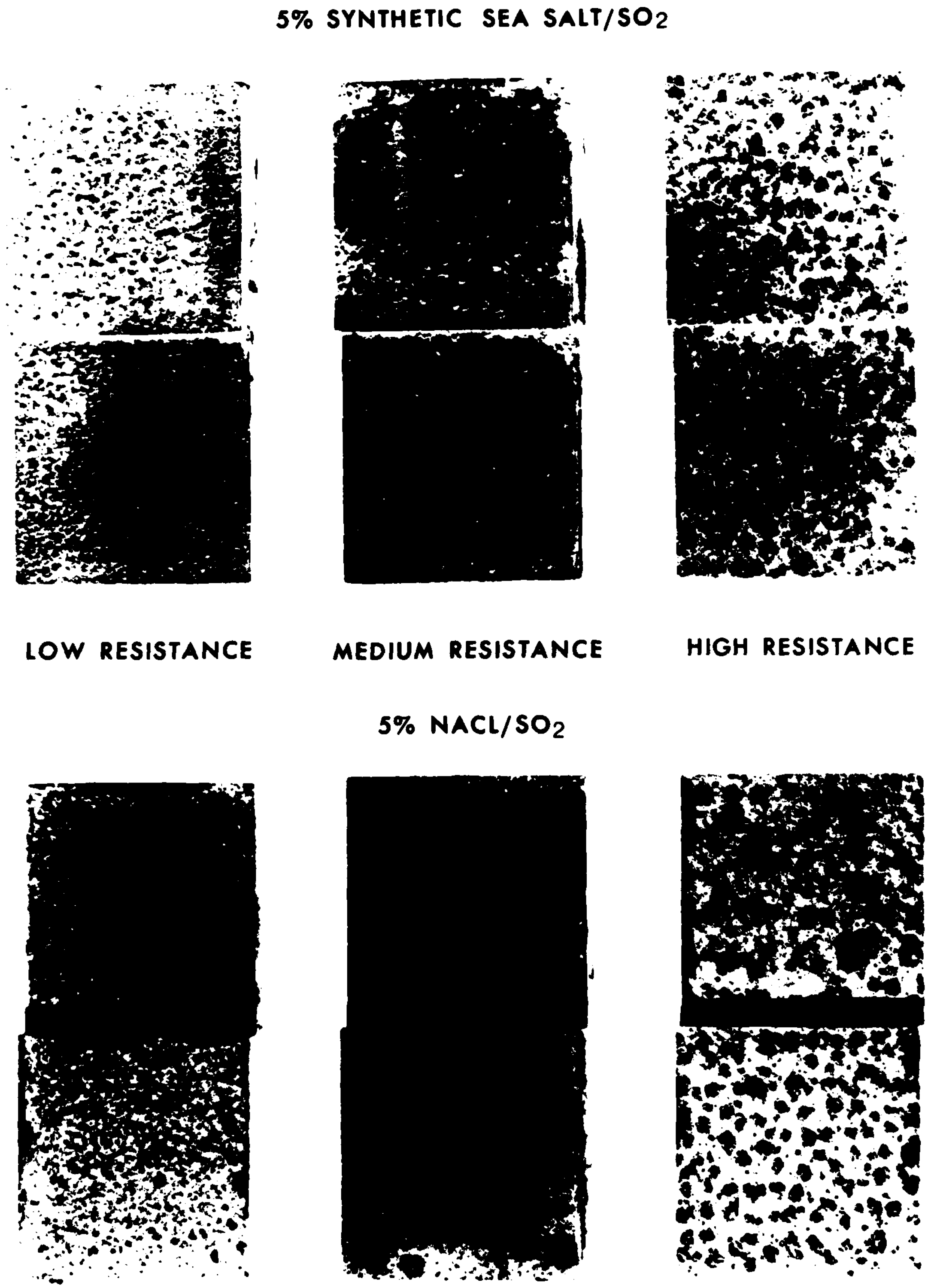


Figure 9 - Results of Salt Spray Tests on 2124 1/2 in. Plate - 10 Days

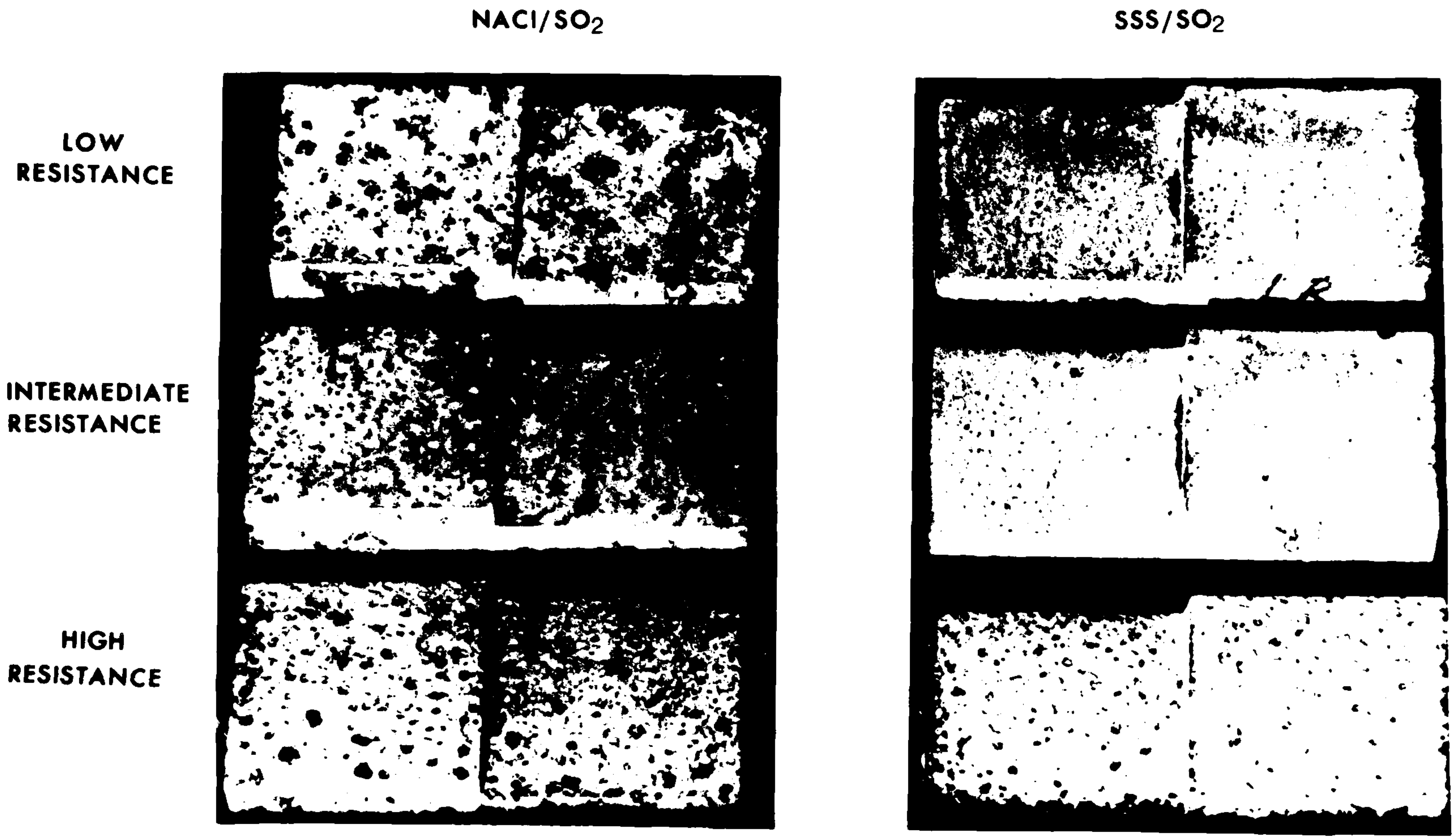


Figure 10 - Results of Salt Spray Tests On 2124 - 1/2 in. Plate - 37 Days.

5% SYNTHETIC SEA SALT/SO_2

LOW RESISTANCE MEDIUM RESISTANCE HIGH RESISTANCE

5% NACl/SO_2

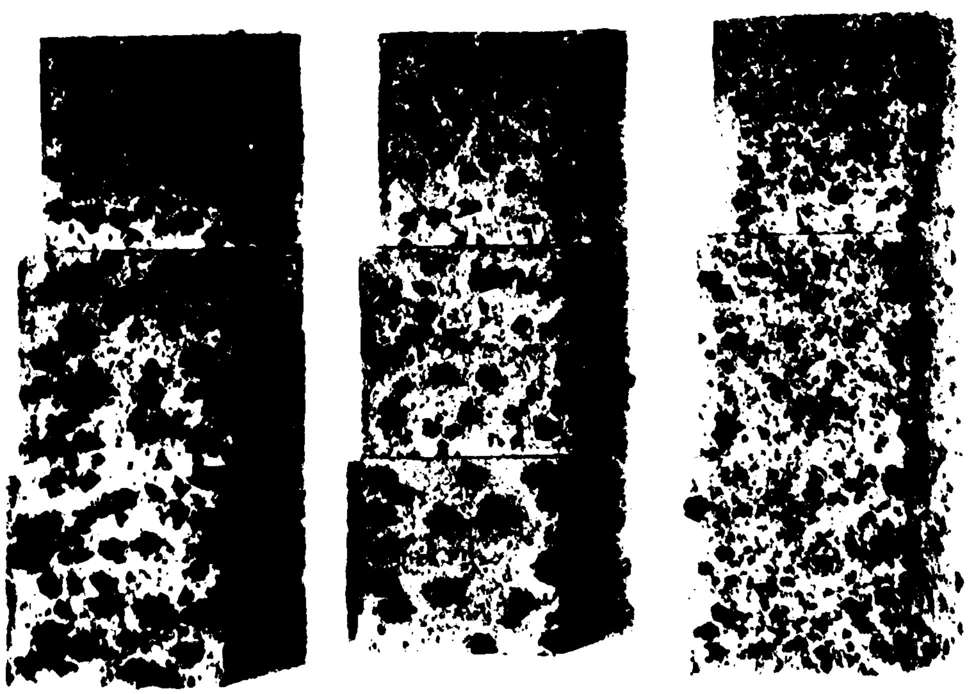


Figure 11 - Results of Salt Spray Tests on 2124 - 2 in. Plate - 10 Days.

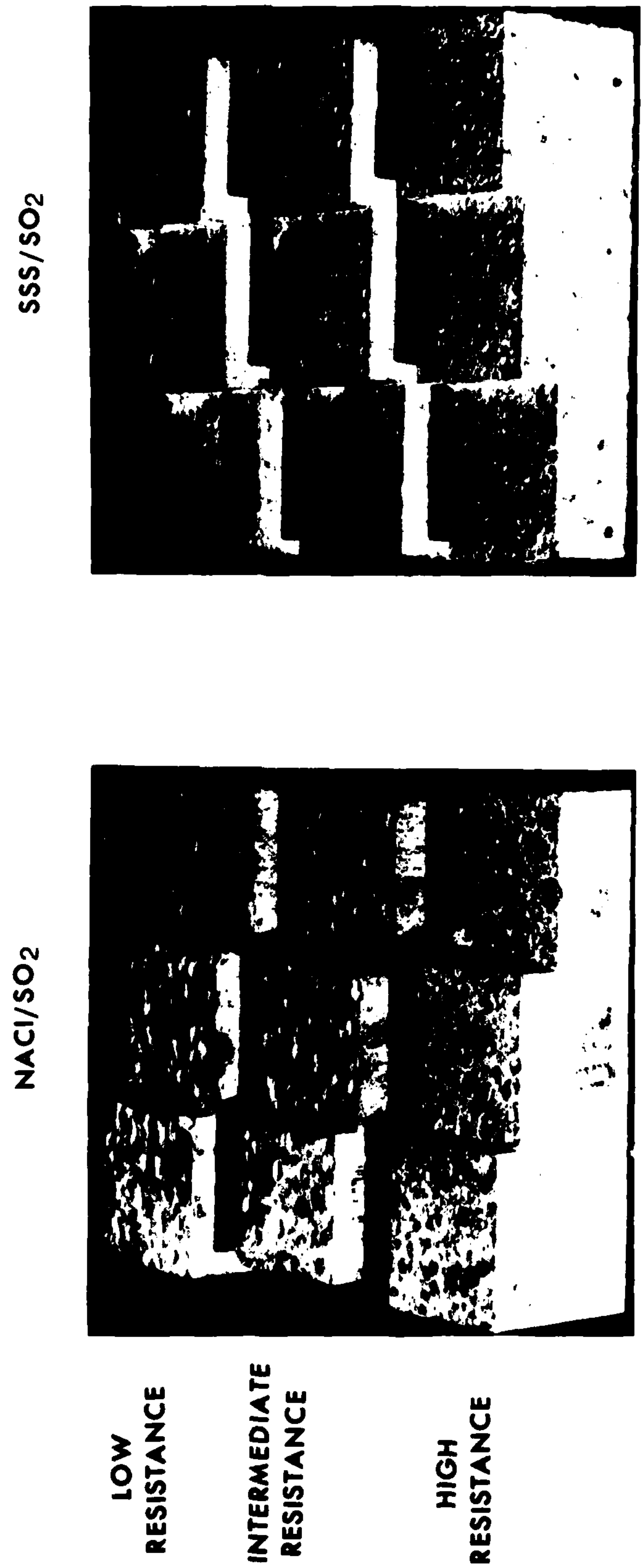


Figure 12 - Results of Salt Spray Tests on 2124 - 2 in. Plate - 37 Days.

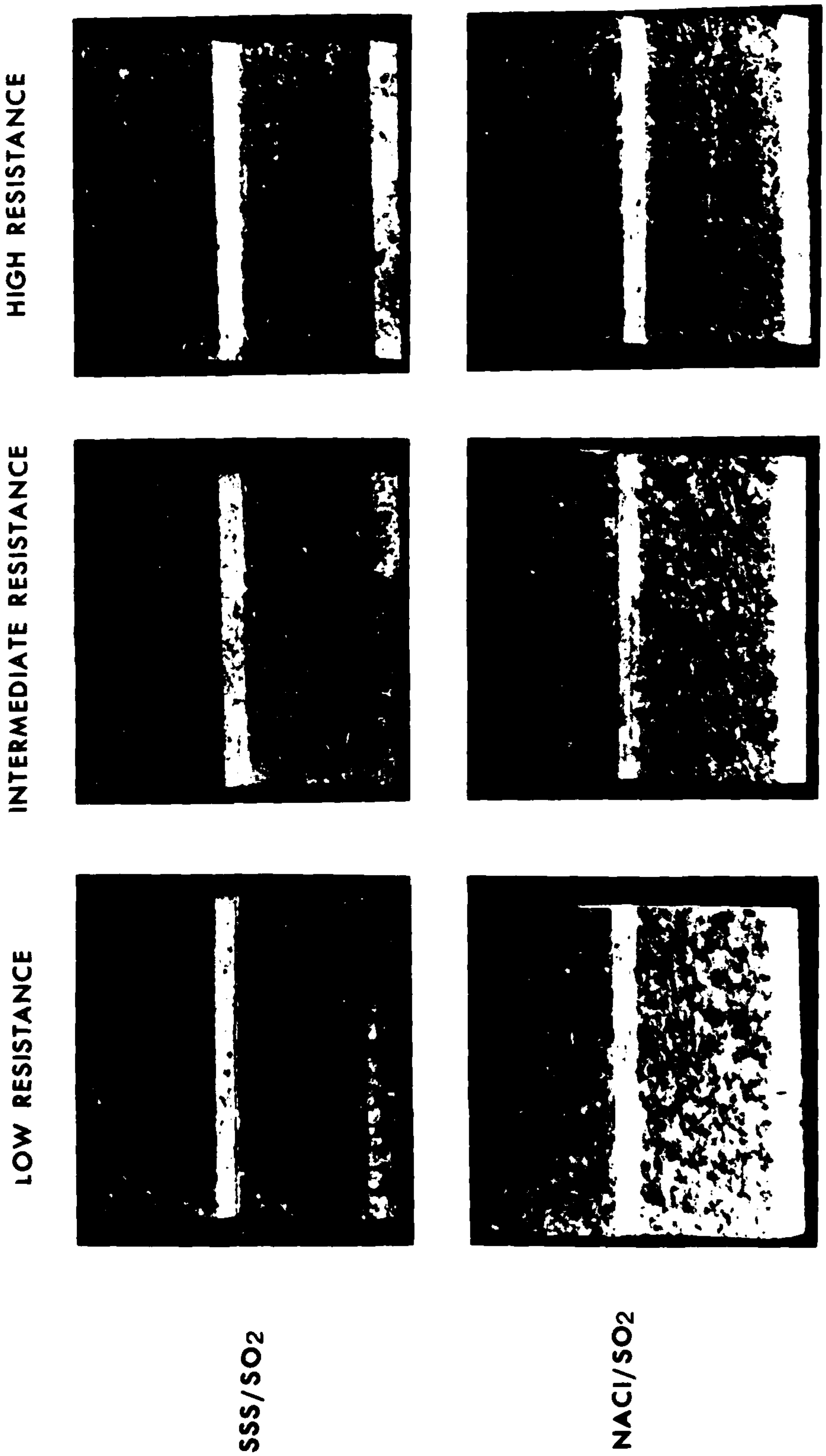
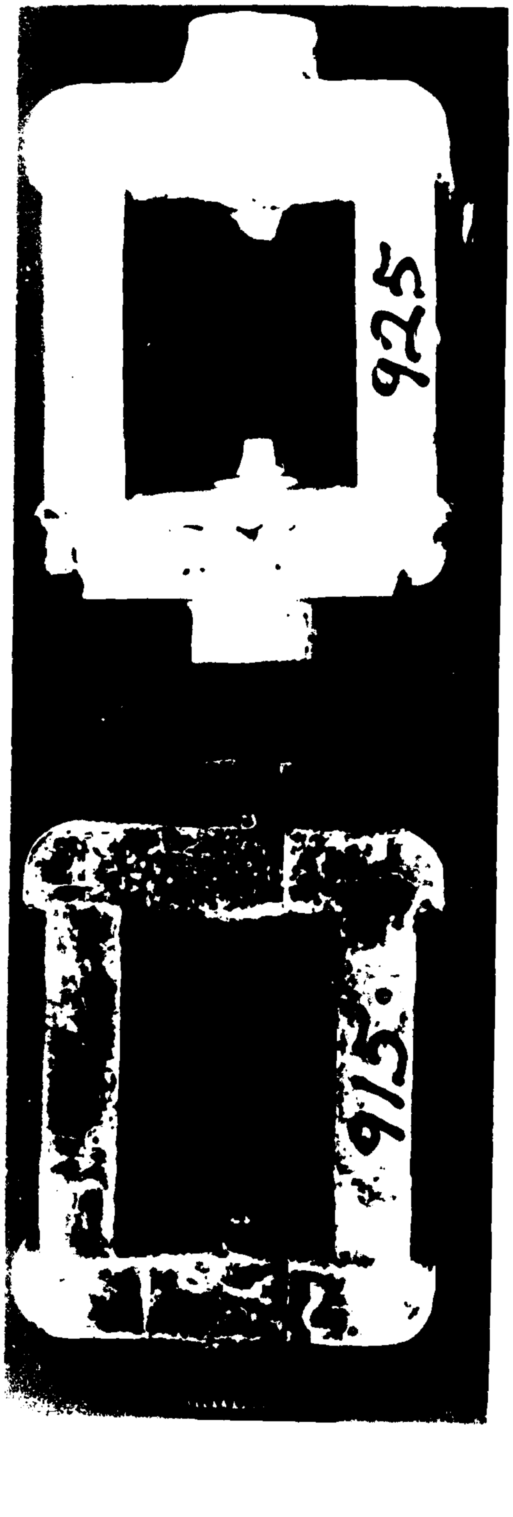


Figure 13 - Results of Salt Spray Tests on 7075 Extrusions - 17 Days.



APPEARANCE AFTER CLEANING

APPEARANCE BEFORE REMOVING DEPOSITS FROM CARRIER

Figure 14 - Stress Corrosion Fixtures.

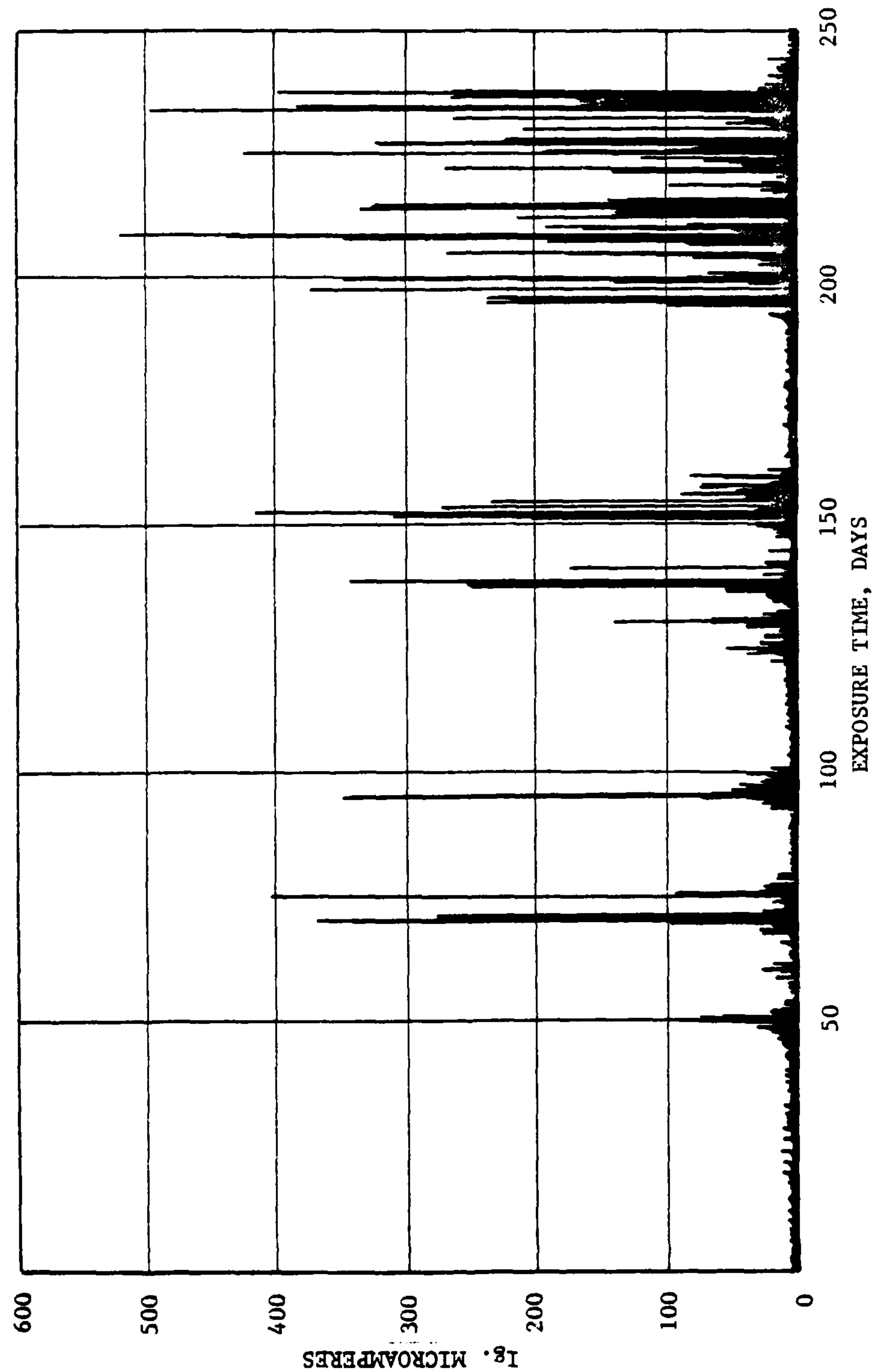


Figure 15 - Corrosion Current - Time Tracing Output From Corrosivity Monitor.

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a. AIRTASK ZF61-542-001, Work Unit ZM501

b. D.O. Sprowls et al, Evaluation of a Proposed Standard Method of Testing for Susceptibility to Stress Corrosion Cracking of High Strength 7XXX Series Aluminum Alloy Products, STP 610, ASTM, Phila. 1976.

c. ANSI/ASTM G-49-76, Standard Recommended Practice for Preparation and Use of Direct Tension Stress Corrosion Test Specimens.

d. F. Mansfeld and J.V. Kenkel, Electrochemical Monitoring of Atmospheric Corrosion Phenomena, Corrosion Science, 16, III (1976).

e. Report No. NADC-77252-30, Accelerated Laboratory Corrosion Test for Materials and Finishes Used in Naval Aircraft of 14 Sep. 77.

f. Joint Aluminum Association - ASTM Task Group on Exfoliation Testing of Aluminum Alloys, Internal Committee Reports.

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